CHAPTER 2

CLASSIFICATION AND CHARACTERIZATION OF LARGE DIAMETER SHAFTS

2.1 SHAFT CLASSIFICATION

The lateral load analysis procedures differ for short, intermediate and long shafts. The short, intermediate and long shaft classifications are based on shaft properties (i.e. length, diameter and bending stiffness) and the soil conditions described as follows. A shaft is considered "short" so long as it maintains a lateral deflection pattern close to a straight line. A shaft classified as "intermediate" under a given combination of applied loads and soil conditions may respond as a "short" shaft for the same soil profile for a different combination of applied loads and degraded soil properties (e. g. a result of soil liquefaction).

The shaft is defined as "long" when $L/T \geqslant 4$. L is the shaft length below ground surface and T is the relative stiffness defined as $T = (EI/f)^{0.2}$ where f is the coefficient of subgrade reaction (F/L^3). The computer Shaft treats the given shaft as a short shaft. The value of relative stiffness, T, varies with EI and f. For a short shaft, the bending stiffness (EI) in the analysis could have a fixed value (linear elastic). The coefficient of subgrade reaction, f, varies with level of deflection and decreases with increasing lateral load. The chart (Fig. 2-1) attributable to Terzaghi (DM 7.2, NAVFAC 1982) and modified by Norris (1986) provides average values of f as a function of soil properties only (independent of pile shape, EI, head fixity, etc).

The shaft behaves as an "intermediate" shaft when $[4 > (L/T) > 2]$. When an intermediate shaft is analyzed as a long shaft it results in overestimated lateral response. It should be noted that the classification of the shaft type in the present study (i.e. evaluation of its relative stiffness, T) is based on the initial bending stiffness of the shaft and an average of the coefficient of subgrade reaction (f) including the free-field liquefaction effect.

The shaft classification for the same shaft my change according to the level loading and the conditions (e.g. liquefied or non-liquefied) of the surrounding soils. In addition, shaft stiffness also varies with level of loading and the induced bending moment along the shaft. Therefore, the criterion mentioned above is not accurate and does not reflect the actual type of shaft with the progressive state of loading. For example, a shaft could behave as a long shaft under static loading and then respond as an intermediate shaft under developing liquefaction. Such response is due to the changing conditions of the surrounding soil. The analysis carried out in this study changes according to the type of shafts.

2.2 FOUNDATION STIFFNESS MATRIX

The structural engineer targets the shaft-head stiffness (at the base of the column) in 6 degrees of freedom as seen in Figs. 2-2 through and 2-4. In reality, the bending stiffness (EI) of the cross section varies with moment. In order to deal with an equivalent linear elastic behavior, a constant reduced bending stiffness (EI_r) for the shaft cross section can be used to account for the effect of the cracked concrete section under applied loads. However, it is very difficult to identify the appropriate reduction ratio for the shaft stiffness at a particular level of loading. The technique presented in this report allows the assessment of the displacement and rotational stiffness based on the varying bending stiffness of the shaft loaded. Such nonlinear modeling of shaft material reflects a realistic representation for the shaft behavior according to the level of loading, and the nonlinear response of shaft material and the surrounding soil The structural engineer can also replace the nonlinear shaft-head stiffnesses shown in Figs. 2-3 and 2-4 by using the shaft foundation and the p-y curve resulting from the presented technique along with the superstructure (complete solution) to model the superstructure-soil-shaft behavior as shown in Fig 2-6.

2.3 LARGE DIAMETER SHAFT

The computer programs LPILE/COM624P have been developed using lateral load tests performed on long slender piles. The Vertical Shear Resistance (V_v) acting along the pile or shaft perimeter has no significant influence on the lateral response of shafts and piles of diameters less than 3 feet. However, V_v contributes significantly to the capacity of large diameter shafts. The shaft analysis presented in this report accounts for the Horizontal and

Vertical Shear Resistance (V_h and V_v) acting along the sides of large diameter shafts in addition to base resistance (Fig. 2-7). The t-z curve for soil (sand, clay, c-φ soil and rock) is evaluated and employed in the analysis to account for the vertical shear resistance.

It should be noted herein that there are basic differences between the traditional p-y curves used with LPILE/COM624P and the Strain Wedge (SW) model technique employed in the current Shaft analysis.

- The traditional p-y relationships used in LPILE/COM624P do not account for the vertical side shear (V_v) acting along the sides of large diameter shafts because these relationships were developed for piles with small diameters where side shear is not significant.
- The traditional p-y relationships used in LPILE/COM624P were developed for long piles and not for intermediate/short shafts or piles. The p-y relationships for long piles are stiffer than those of short piles/shafts and their direct use in the analysis of short shafts is not realistic.
- The traditional p-y relationships for sand used in LPILE/COM624P are multiplied, without any explanation, by an empirical correction factor of 1.55 (Morrison and Reese, 1986)
- The bending stiffness of the pile/shaft has a marked effect on the nature of the resulting p-y curve relationship. The traditional p-y relationships used in LPILE/COM624P do not consider this effect. That is, the traditional p-y relationships used in LPILE/COM624P were developed for piles with diameters less than 3 feet that have much lower values of bending stiffness (EI) than the large diameter shafts.
- The traditional p-y curves for sand, developed about 30 years ago, is based on a static load test of a 2-ft diameter long steel pipe pile. They do not consider soil liquefaction.
- The traditional p-y curves have no direct link with the stress-strain relationship of the soil. Therefore, it is not feasible to incorporate the actual stress-strain behavior of liquefied soil in the traditional p-y curve formula.
- The traditional p-y curve cannot account for the varying pore water pressure in liquefied soil. It can only consider the pore water pressure ratio (r_u) in the free field (away from the shaft) by reducing the effective unit weight of soil by a ratio equal to r_u. Because of

this limitation, the traditional p-y curve, even after modification via r_u, is incapable of modeling the increase in pore water pressure around the shaft from the added superstructure loading.

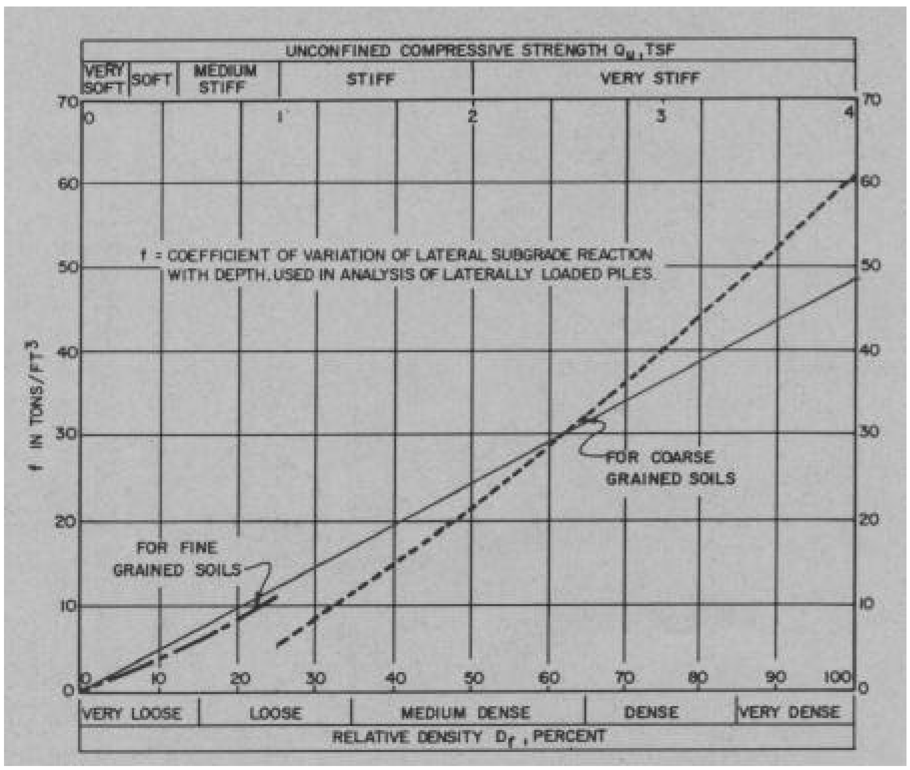


Fig. 2-1 f vs. q_u for Fine Grained Soil and f vs. D_r for Coarse Grained Soils

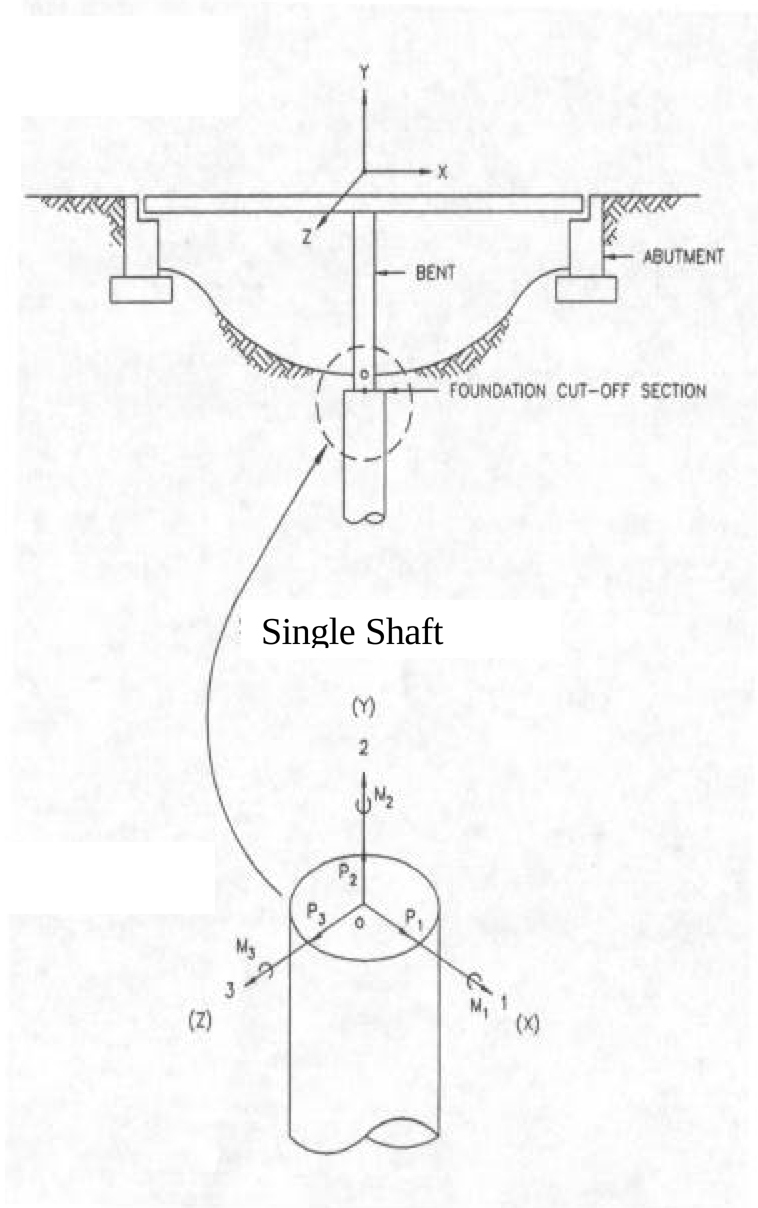
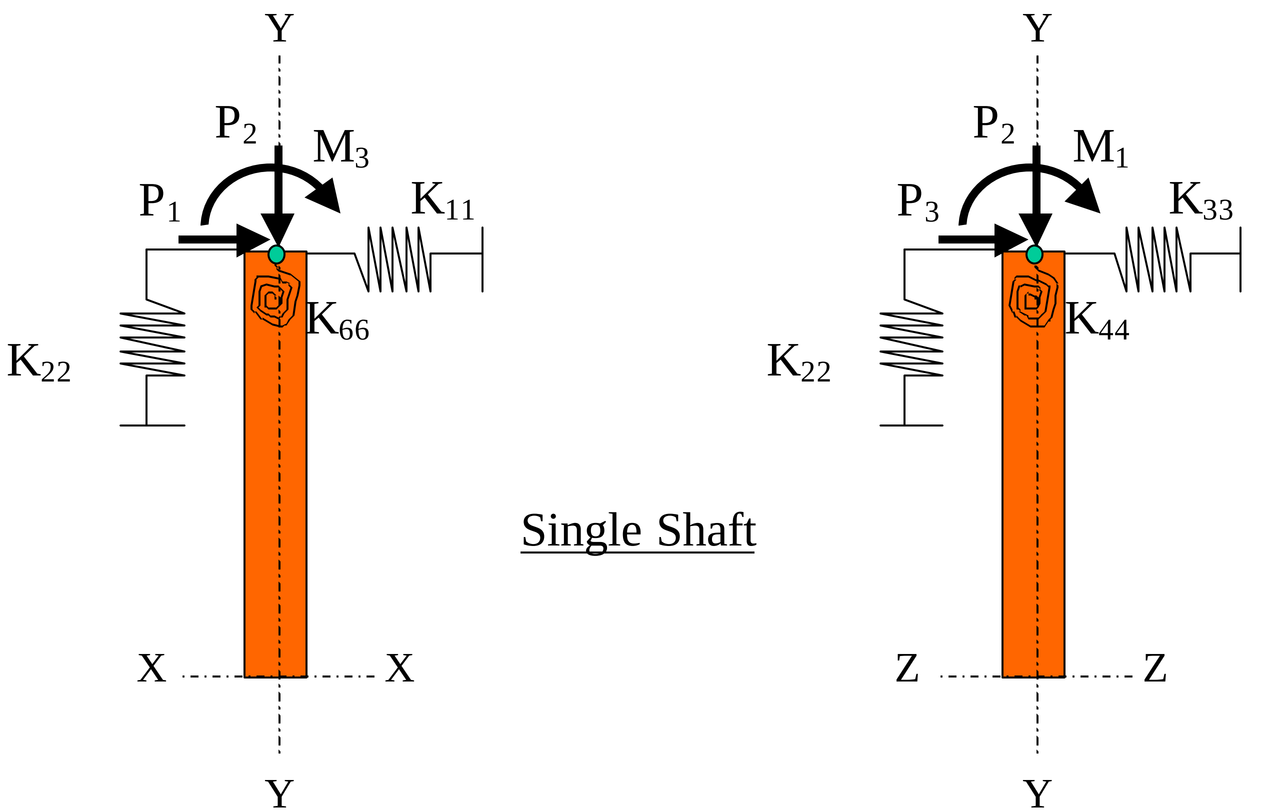


Fig. 2-2 Bridge Shaft Foundation and Its Global Axes



A) Loading in the X-X Direction
(Axis 1)

B) Loading in the Z-Z Direction
(Axis 3)

Fig. 2-3 Foundation Stiffnesses for a Single Shaft

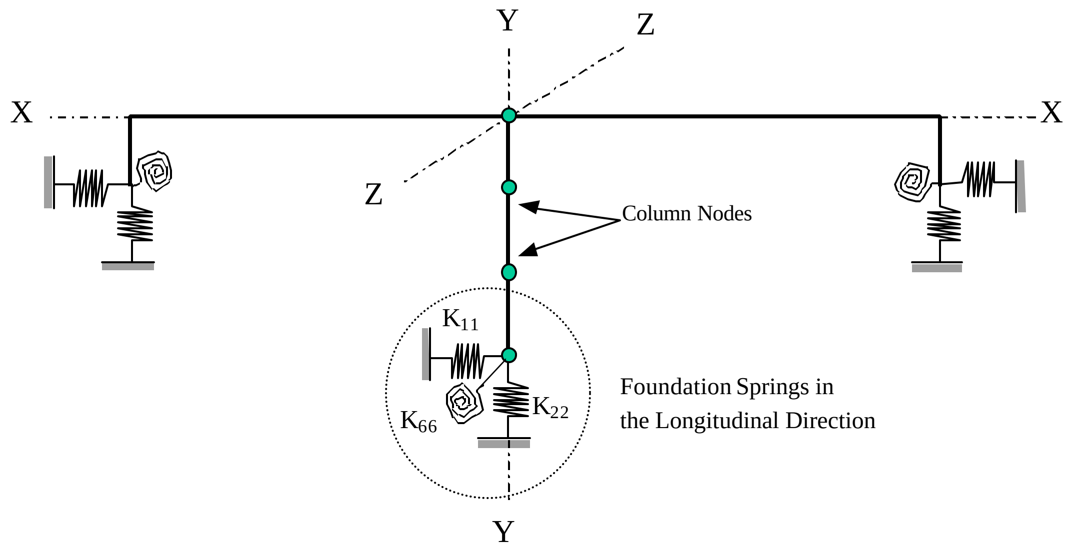


Fig. 2-4 Foundation Springs at the Base of a Bridge Column in The X-X Direction.

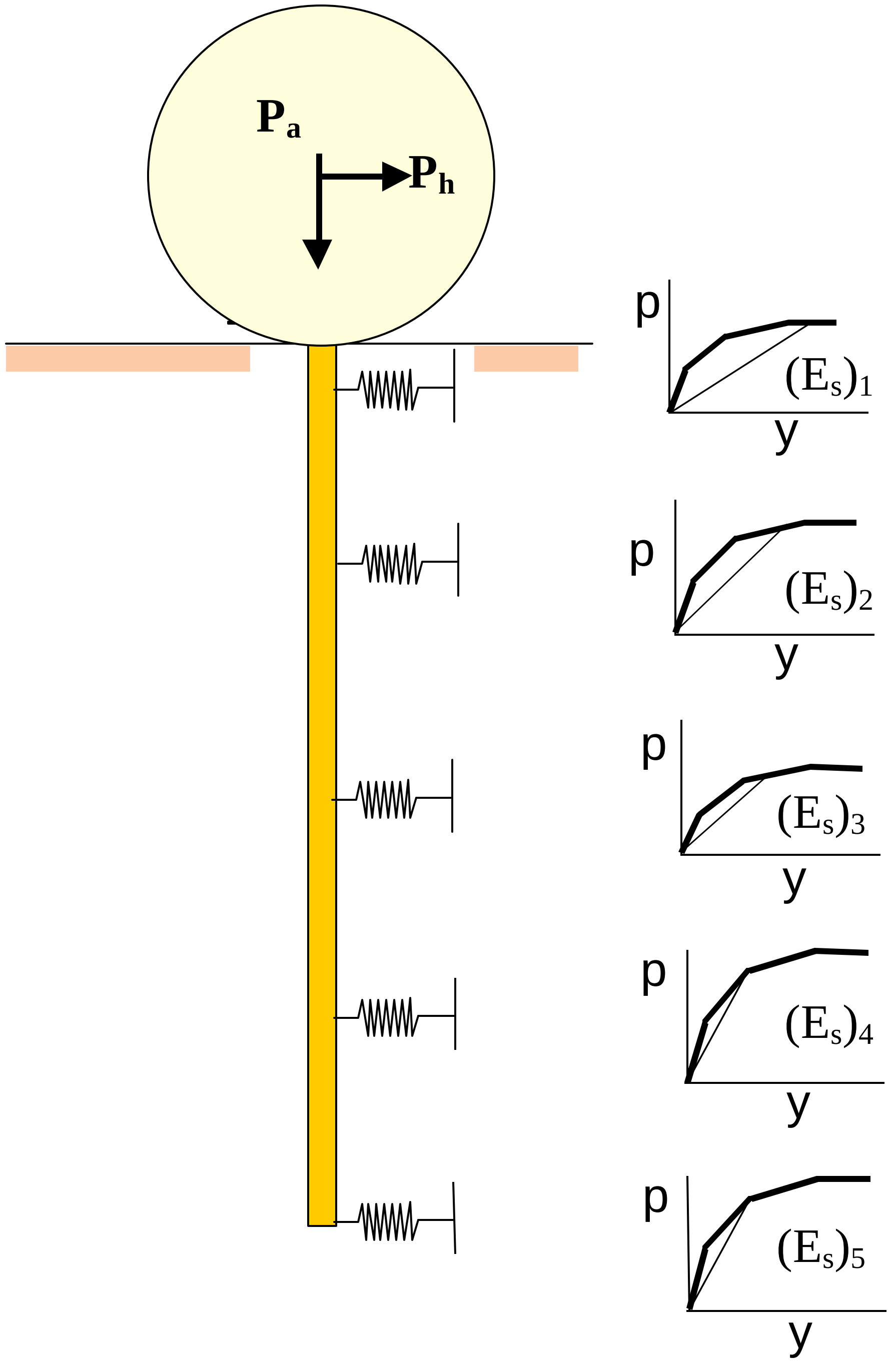


Fig. 2-6 Superstructure-Shaft-Soil Modeling as a Beam on Elastic Foundation (BEF)

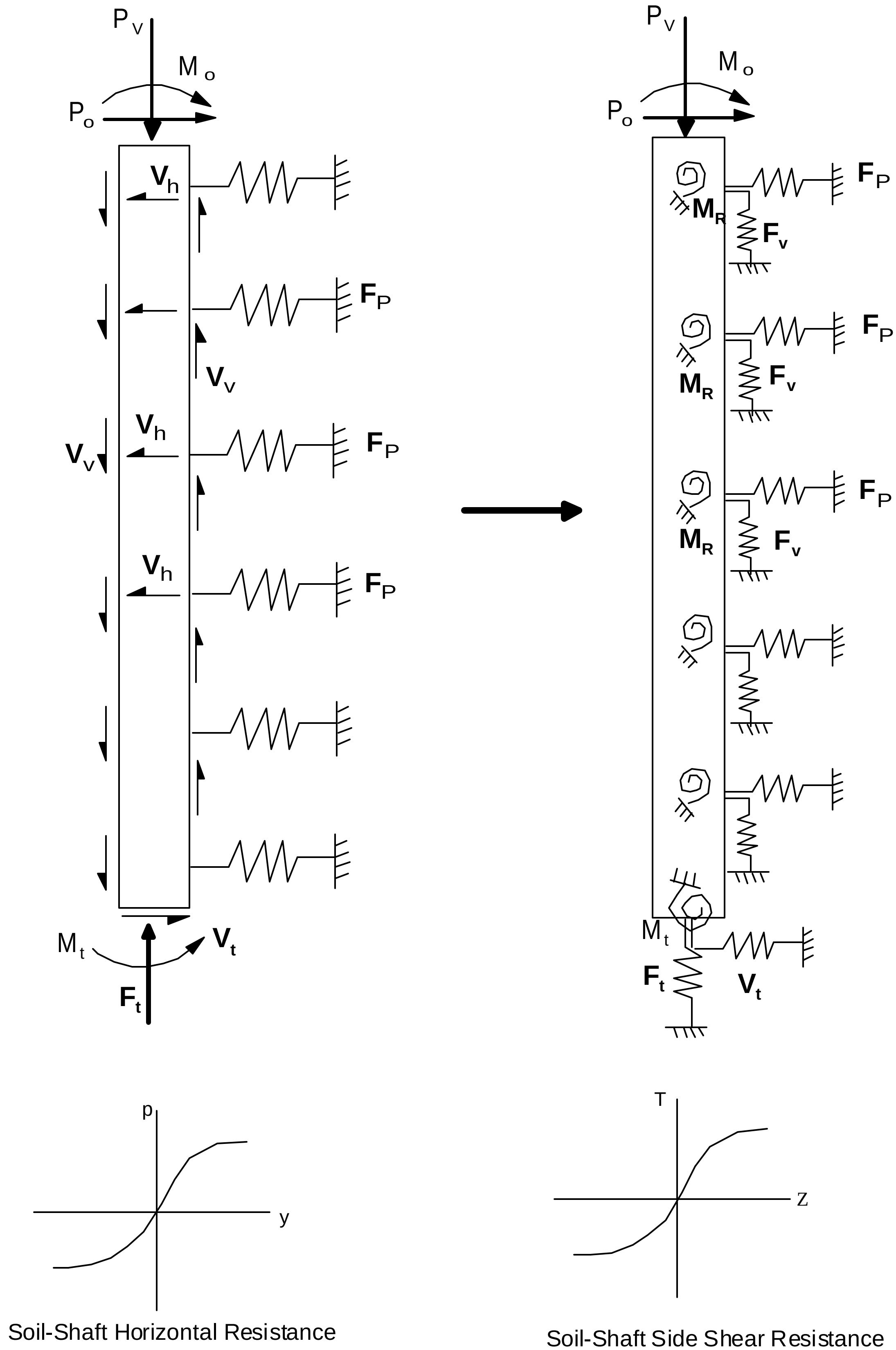


Fig. 2-7 Configuration of a Large Diameter Shaft